Ecological Indicators 85 (2018) 887–903

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Persistent negative changes in seasonal greenness over different forest types of India using MODIS time series NDVI data (2001–2014)

Abhishek Chakraborty*, M.V.R. Seshasai, C. Sudhakar Reddy, V.K. Dadhwal

National Remote Sensing Centre, Indian Space Research Organisation, Balanagar, Hyderabad, 500 037, India

ARTICLE INFO

Keywords:
Forest greenness
Negative change
Time series NDVI
Hotspots

ABSTRACT

This study assessed the spatial patterns of significant negative trend of forest seasonal greenness over the different forest types of India using 8-day composite MODIS NDVI (500 m) time series data (2001–2014). It was further analyzed to quantify the negative changes in the core forest areas and to indentify hotspots of it over the large protected forest areas. Significant negative changes in the seasonal greenness were found to be highest over tropical moist deciduous forest (2067.35 thousand ha) followed by tropical dry deciduous (1407.73 thousand ha), tropical wet evergreen (577.43 thousand ha), tropical semi evergreen (442.58 thousand ha), subtropical broad leaved (321.13 thousand ha) and Himalayan moist temperate forest (293.80 thousand ha). Mangroves forest also showed decrease in its greenness over 15.6% of its total area. Interestingly, most of the observed negative changes of high to medium magnitude were found in the core areas of the forest types. Hotspots analysis revealed spatially coherent significant negative changes of seasonal greenness over the large protected areas i.e. Similipal wildlife sanctuary of Odisha, Rajaji national park of Uttarakhand, Achanakmar wildlife sanctuary of Chhattisgarh and Sundarban of West Bengal. The outcomes of the present study would help in the prioritization of the forest types and protected forest areas for biodiversity conservation and climate change mitigation programmes.

1. Introduction

There is an increasing scientific consensus that natural vegetation systems are facing unprecedented risk due to anthropogenic activities and climatic change (Midha and Mathur, 2010). Negative changes in forest vigour and deforestation has huge ramifications on carbon stocks, biodiversity, ecosystem services and livelihoods of dependent people. According to the IPCC AR5 report, the net annual carbon emission was estimated to be 3.3 billion tonnes of CO_2 from deforestation during the past decade (http://www.ipcc.ch). The loss of ecosystem services has been identified by the United Nations as the greatest challenge to the humankind as it slows down the economic development of a nation, thus intricately linked to poverty (Díaz et al., 2006). The entities at threat include ecosystem, population, physical and biological processes (Kaly et al., 2002). Thus to mitigate the menace of climate change, the Reducing Emissions from Deforestation and forest Degradation (REDD +) has gained importance as a implementable strategy at multiple scales (Lin et al., 2014).

As per the definition of the Food and Agricultural Organization of the United Nations, forest degradation is a process that leads to temporary or permanent deterioration in the density, structure of vegetation or its species composition, and thus to a lower productive capacity of forest (FAO, 2011). The different indicators of forest degradation include: high fragmentation, negative change in forest canopy cover, reduction of biomass, shifting cultivation, unsustainable logging, frequent fires, decline in species population, invasion of alien species and loss of soil fertility. Subtle changes in forest vigour can be identified by analysing changes in its seasonal greenness using vegetation phenology. Vegetation phenology is a study of recurring patterns of vegetation growth and development. The impact of climate change on ecosystem can be successfully assessed by the changes of vegetation phenology (White et al., 1997). Variations in vegetation phenology alter global carbon, water and nitrogen cycles, crop production, duration of pollination season and distribution of diseases and pests, thus has broad impact on terrestrial ecosystems and human societies (Penuelas and Fiella, 2001; Soudani et al., 2008). Therefore, the ecological and climatic research has given special emphasis to the study of phenological changes of vegetation (Menzel et al., 2001; Cleland et al., 2007). There are three possible ways to assess vegetation phenological events *i.e.* '*in situ*' observations, bioclimatic models and remote sensing techniques (Schaber and Badeck, 2003; Fisher et al., 2007). The *in situ* observations are expensive, time consuming, subjected to operators bias

* Corresponding author.
E-mail address: jeet.abhishek@gmail.com (A. Chakraborty).

https://doi.org/10.1016/j.ecolind.2017.11.032
Received 17 March 2017; Received in revised form 17 November 2017; Accepted 17 November 2017
Available online 28 November 2017
1470-160X/ © 2017 Elsevier Ltd. All rights reserved.

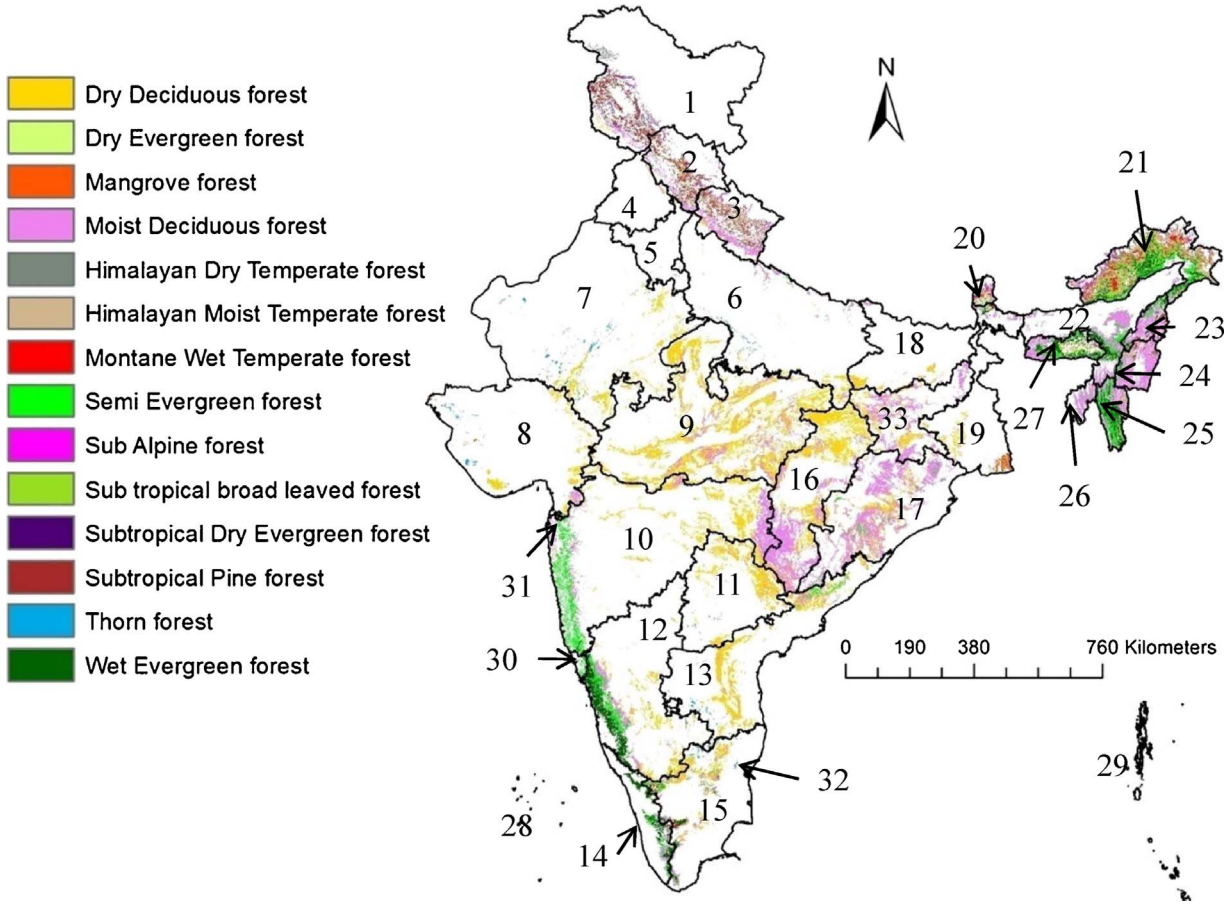

Fig. 1. Forest types of India (Reddy et al., 2015). Selected Indian states and union territories of the present study: 1 Jammu & Kashmir, 2. Himalchal Pradesh, 3. Uttarakhand, 4. Punjab, 5. Haryana, 6. Uttar Pradesh, 7. Rajasthan, 8 Gujarat, 9. Madhya Pradesh, 10. Maharashtra, 11. Telangana, 12. Karnataka, 13. Andhra Pradesh, 14. Kerala, 15. Tamil Nadu, 16. Chhatisgarh, 17. Odissa, 18. Bihar, 19. West Bengal, 20. Sikkim, 21. Arunachal Pradesh, 22. Assam, 23. Nagaland, 24 Manipur, 25. Mizoram, 26 tripura, 27. Meghalaya, 28. Lakshadweep, 29. Andaman & Nicobar island, 30. Goa, 31. Dadra & Nagar Haveli, 32. Pondicherry, 33. Jharkhand.

and thus difficult to extent to large geographical areas. Bioclimatic models require accurate and exhaustive vegetation and climatic data specific to forest species along with local calibration to extend it over large scales. Satellite remote sensing is a proven viable alternative which could provide regular, even daily, monitoring of the entire global land surface. The satellite gather data about entire ecosystems or regions rather than individual species over its footprint, thus could provide a unique perspective of earth surface. Satellite remote sensing can reveal broad-scale phenological changes that would be difficult, if not impossible, to detect from the field survey. Satellite data can be standardized and calibrated across the sensor to provide continuous information over large temporal span. Thus satellite remote sensing technique has emerged as a cost effective alternative of phenological study with good temporal repeatability over large and inaccessible regions.

There have been many studies of changes in vegetation phenology in different parts of the globe using *in situ* observations. The advancement of spring phenophages and significant increase in the length of growing season of deciduous tree over Germany during the period of 1951–1996 was reported by Menzel et al., 2001. The phenological data of six major phenophases of 29 species over Spain for the period of 1943–2003 were analyzed by Gordo and Sanz 2009, and found advancement of the dates of leaf folding, flowering, and fruiting in few species. They have also reported that wind pollinated species have advanced their flowering more than the insect and animal pollinated plants.

Extensive research works were conducted to find out the changes in vegetation phenology using remote sensing techniques. Vegetation phenology is usually addressed through temporal monitoring of the satellite derived Normalized Difference Vegetation Index (NDVI) time series. The NDVI is calculated as the normalized relative difference between near-infrared and red bands. The NDVI quantifies the photosynthetic capacity of plant canopies, thus represents the amount of vegetation present in one place. Moderate to coarse resolution satellite sensor, which is generally preferred in phenological studies for its high repeativity, cannot provide the phenological events directly, rather different phenology analogues such as start of the growing season (SGS), end of the growing season (EGS), length of the growing season (LGS), seasonal NDVI amplitude (AMP), seasonally integrated NDVI etc could be derived. Time series NDVI had been used to detect positive trends of LGS over North America and Eurasia (Zhou et al., 2001), changes of vegetation activities over Europe (Stockli and Vidale, 2004), Central Asia (De Beur and Henebry, 2004), Inner Mongolian steppe (Lee et al., 2002), Sahel & Soudan (Heumann et al., 2007), China (Piao et al., 2006; Fang et al., 2003), and India (Chakraborty et al., 2014).

India is one of the mega-biodiversity countries having an area of 328.72 Mha. Reddy et al. (2013a) has reviewed the works on the forest cover changes in India. The study has contributed to the understanding of spatial patterns of forest fragmentation in India (Reddy et al., 2013b). Reddy et al. (2016) has carried out quantitative analysis of deforestation in India over eight decades (1930–2013). Single or two date mapping of forest degradation is not meaningful for the evaluation of status of forest without having continual time series information. All the previous studies on the forest cover change mainly involved in analysis of changes between two or more time epoch. The continuous process of changes in the forest greenness using time series satellite

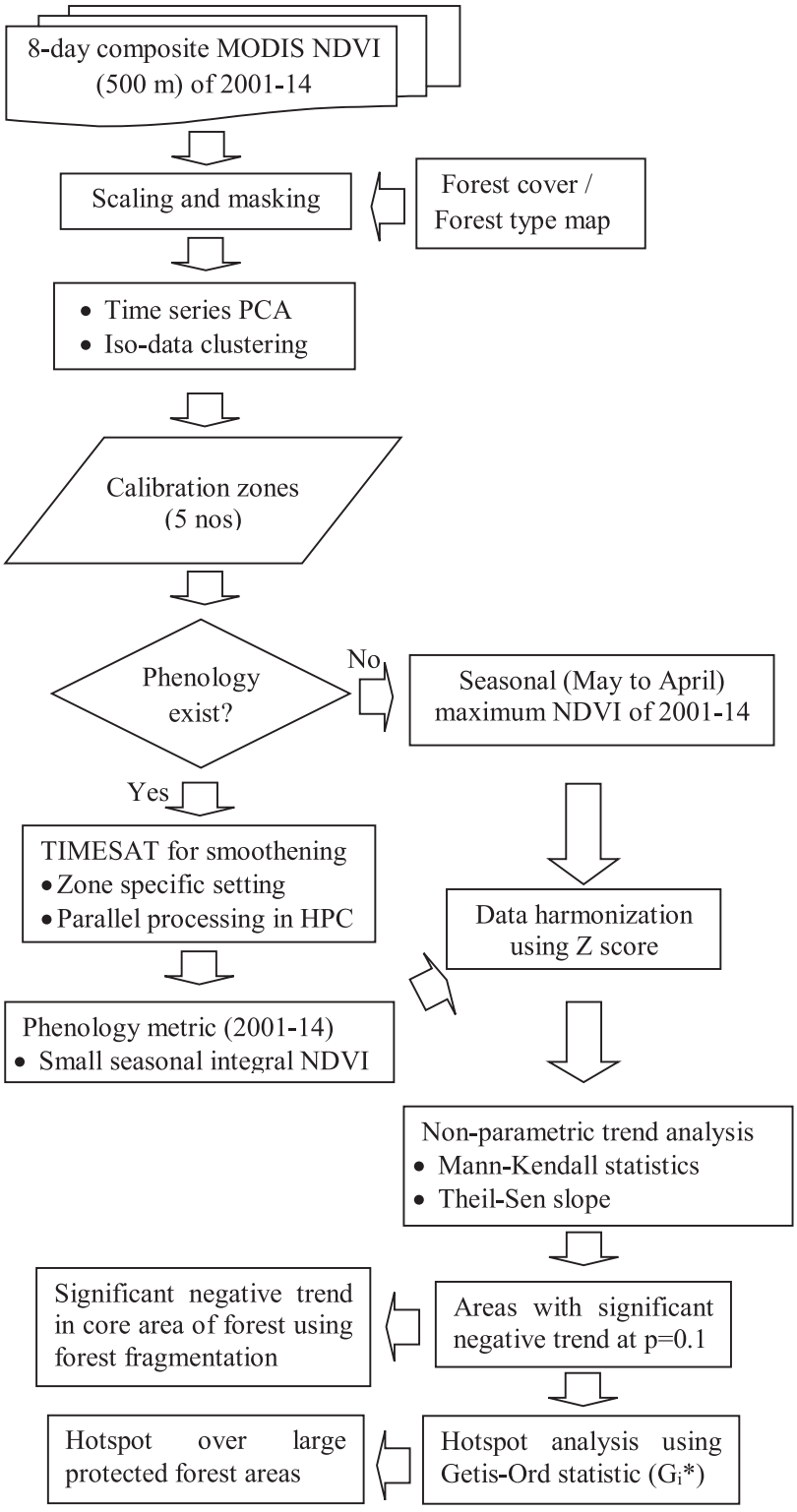
8-day composite MODIS NDVI (500 m) of 2001-14
Scaling and masking
Forest cover / Forest type map
• Time series PCA
• Iso-data clustering
Calibration zones (5 nos)
Phenology exist?
No
Seasonal (May to April) maximum NDVI of 2001-14
Yes
TIMESAT for smoothening
• Zone specific setting
• Parallel processing in HPC
Data harmonization using Z score
Phenology metric (2001-14)
• Small seasonal integral NDVI
Non-parametric trend analysis
• Mann-Kendall statistics
• Theil-Sen slope
Significant negative trend in core area of forest using forest fragmentation
Areas with significant negative trend at p=0.1
Hotspot over large protected forest areas
Hotspot analysis using Getis-Ord statistic (Gi*)

Fig. 2. Schematic diagram of the methodology followed in the present study.

observations has not been performed. Study of forest phenology, its greening and browning patterns, has potential to throw light in the process of forest growth and decline. The temporal trend of the forest greenness in a decadal time frame could provide us persistent changes in the forest vigour which could be a robust surrogate of forest degradation.

In the present study, 8 days composite MODIS NDVI (500 m) data set were used for the period of 2001–2014 to assess the significant negative trend of seasonal greenness of natural vegetation of India. MODIS NDVI time series data were analyzed to its fullest capacity to extracted forest phenology metric of seasonal greenness, its dynamics and non-parametric trend. Spatial analysis of significant decrease in forest greenness along with its magnitudes were quantified over different forest types and core forest areas, which intern provided the hotspots of major negative changes of forest greenness over the large protected areas.

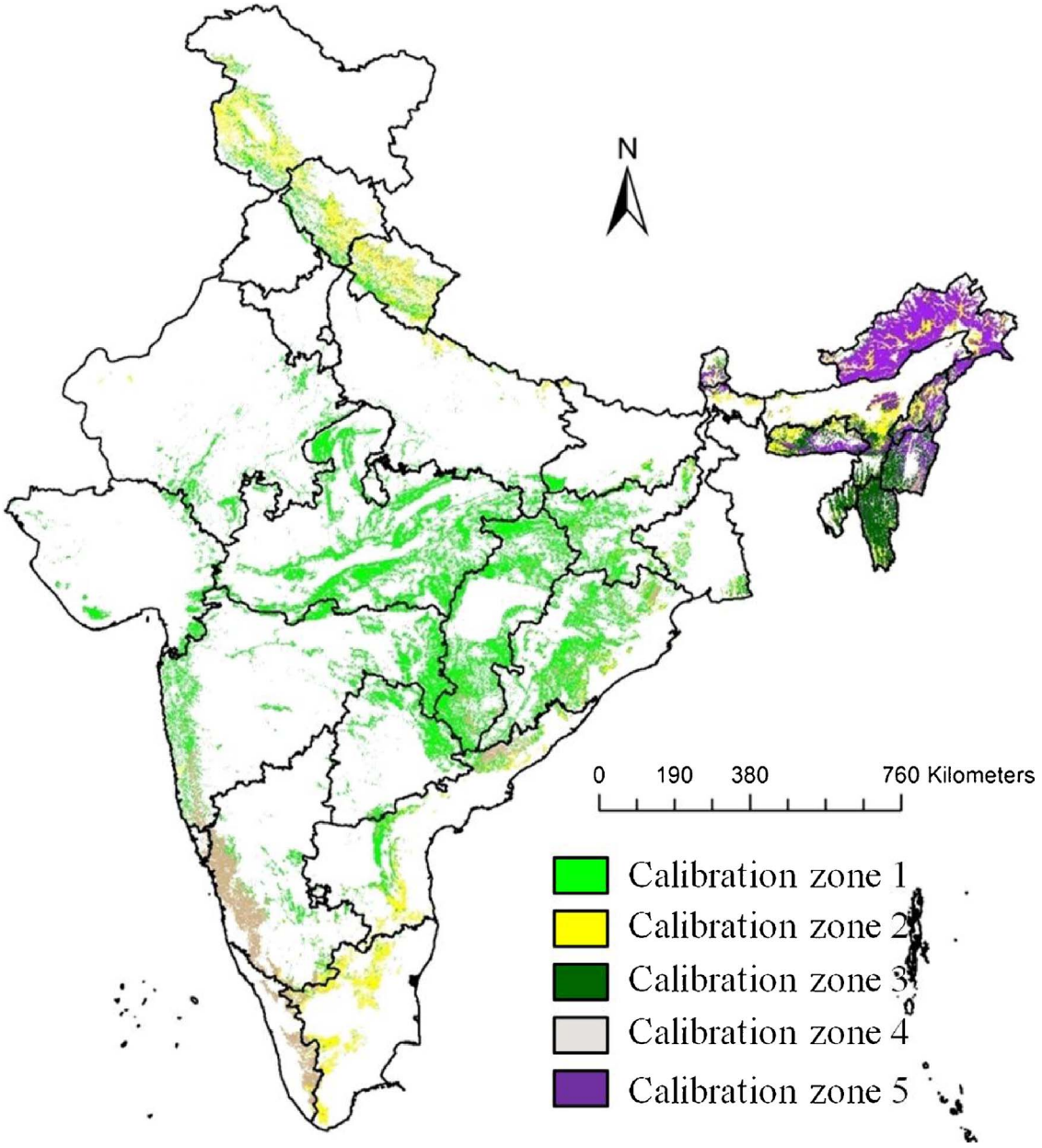

Fig. 3. Different calibration zones of the study area derived from time series principal component analysis.

2. Study area

The present study was carried out over the different forest types of India. Following Champion and Seth's scheme, Reddy et al. (2015) classified Indian forests into 14 forest types based on multi-season satellite images, biogeography, climate, elevation and field data. The forest type map was generated at 56 m spatial resolution. It was aggregated to 500 m spatial resolution using majority rule to match the scale of MODIS NDVI, which was used to assess the significant negative trend of forest greenness. The map of 14 forest types along with the different Indian states (with significant area under forest) of the present study were presented in Fig. 1. Wet Evergreen and semi evergreen forests are present mainly in the high rainfall areas of Western Ghats, Andaman & Nicober Islands and north eastern region. Central India is mainly dominated by dry and moist deciduous forests. Mangroves are found in the coastal region of West Bengal, Odisha, Andhra Pradesh, Tamil Nadu, Maharashtra, Goa and Gujarat. Montane, sub-alpine and sub-tropical pine forests are distributed in the high altitude of Himalayan and north-east regions.

3. Methodology

A schematic diagram of the methodology followed in the present study is presented in Fig. 2.

3.1. Data preparation

MODIS 8-days composited surface reflectance product (MOD09A1) pertaining to Indian sub-continent (9 tiles) was downloaded from the Land Processes Distributed Active Archive Centre (LP DAAC) for the year 2001–2014. MOD09A1 provides seven optical bands (Blue, Green, Red, Near Infrared (NIR), and 3 Shortwave Infrared bands) of 500 m spatial resolution in HDF format. The data set were imported in ERDAS imagine software and reprojected in Lambert Conical Conformal projection with necessary scale factor. The NDVI was calculated using normalized differences of NIR and Red band. Cloud masking was

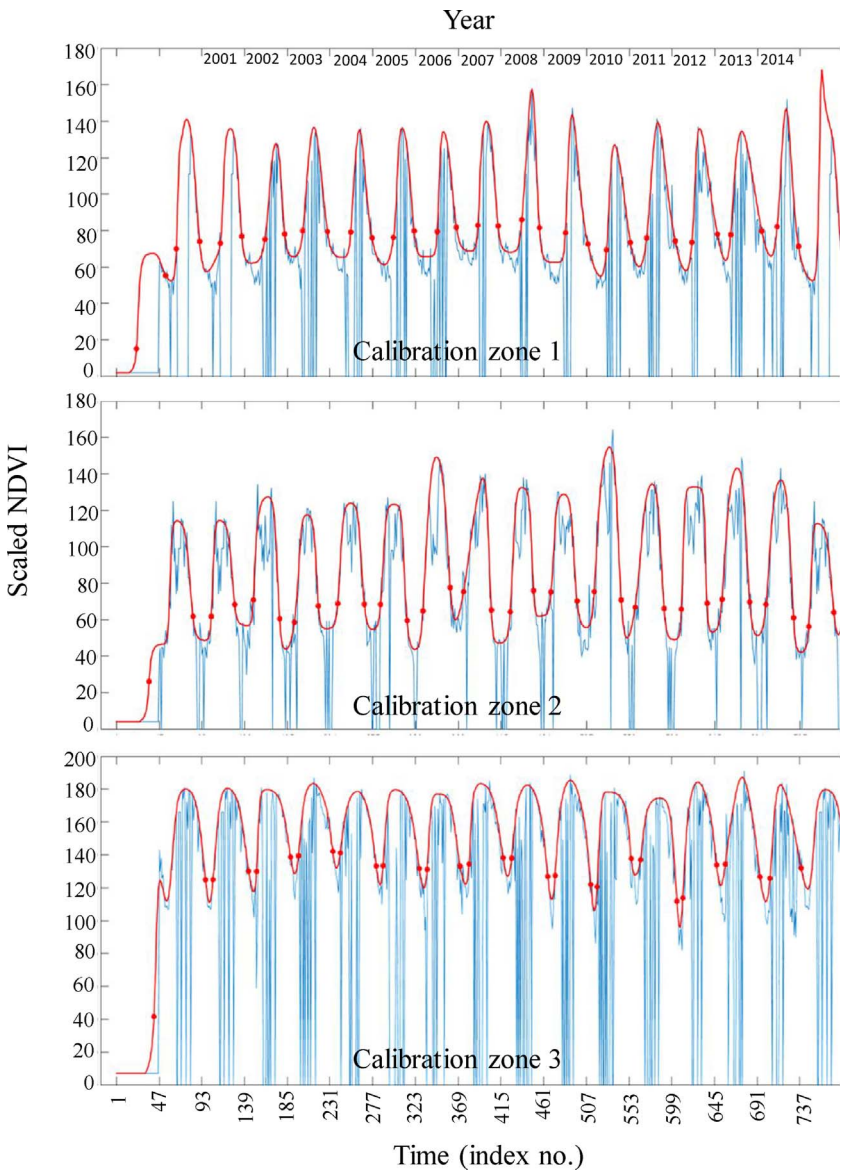
Year
2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
Calibration zone 1
Calibration zone 2
Calibration zone 3
Scaled NDVI
Time (index no.)

Fig. 4. Temporal variation of 8 days composite NDVI during 2001–2014 over a single pixel of calibration zones exhibiting phenology. Blue line represents original scaled NDVI values. Red line represents fitted/smoothened NDVI values. Cloudy pixels are allotted zero value. Time index 1–46 represents calibration zone number, whereas 46–92 and 737–782 correspond to two dummy years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

performed using the blue band of MOD09A1 product. Forest cover mask was prepared from forest type map and non-forest areas were removed from the study area. NDVI values were scaled between 0 and 200, where 0 represents cloud value or non-vegetated pixel and 200 is the highest value NDVI could achieve. Each year consisted of 46 layers of NDVI images, which were stacked with time synchrony to obtain a time series of 2001–2014 (total 644 images).

3.2. NDVI time series principal component analysis

The temporal NDVI profile basically captures the phenology of the forest. Thus it varies greatly over the different forest types. A single technique/equation to smoothen the NDVI temporal profile over the different forest types may not hold good. Thus, the study area was divided into different calibration zones, based on NDVI time series principal component analysis (TS-PCA) (Heumann et al., 2007; Chakraborty et al., 2014). NDVI images of the year 2003, 2006 and 2010 (probable normal years) were selected to perform TS-PCA. Each year consists of 46 images, thus TS-PCA was done using 138 layers. First thirteen principal components (PC) explained 99.08% of variance. Five zones for calibration were identified iteratively by isodata clustering technique using these first thirteen principal components. These five calibration zones had five distinct temporal responses of NDVI. The calibration zones over India were shown in Fig. 3. These calibration zones were created to achieve zone specific fitting function to smoothen the NDVI temporal profile. Among these five zones, three (i.e. calibration zone 1, 2, 3) exhibited distinct pattern of vegetation phenology (Fig. 4). Other two zones did not show any phenology as it covered areas with evergreen type forest (Fig. 5).

3.3. Processing of data in TIMESAT

The TIMESAT software was used to generate smooth time series of NDVI as well as to extract the vegetation phenology metrics for the study area (Jönsson and Eklundh, 2002, 2004; Eklundh and Jönsson,2012). The double logistic equation was used with different seasonality parameters, envelope adaptation strengths, and differential weight to NDVI ranges to smoothen of temporal NDVI profile over the different calibration zones. Calibration zone specific settings of the fitted equations were presented in Table 1. The original scaled NDVI and fitted NDVI pertained to different calibration zones are presented in Fig. 4. Most of the noises in NDVI and other vegetation indices generated from remotely sensed land data are negatively biased. Thus proper care was taken to put least weightage to the cloud and lower NDVI

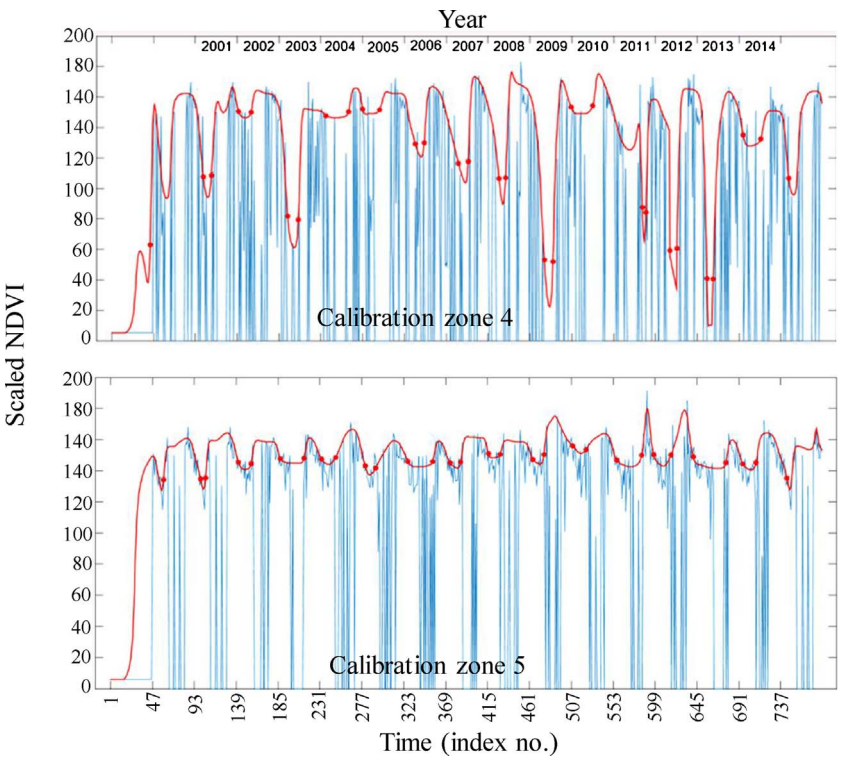

Fig. 5. Temporal variation of 8 days composite NDVI during 2001–2014 over a single pixel of calibration zones exhibiting no phenology. Blue line represents original scaled NDVI values. Red line represents fitted/smoothened NDVI values. Cloudy pixels are allotted zero value. Time index 1–46 represents calibration zone number, whereas 46–92 and 737–782 correspond to two dummy years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Variable settings over different calibration zones for smoothening NDVI temporal profile.

Calibration zones	Seasonality parameters	Envelope criteria		Weight over different ranges of NDVI values (NDVI scaled to 0–200)	
		No. of envelop iteration	Adaptation strength		
1	0.3	3	5	0–20	0.01
				21–80	1
				81–200	1
2	0.3	3	2	0–20	0.01
				21–100	1
				101–200	1
3	0.3	3	5	0–80	0.01
				81–120	1
				121–200	1

values, whereas higher NDVI are considered to be pure pixel values. Zone specific fitting function was arrived iteratively by sampling group of pixel from the calibration zone and plotting it in the TIMESAT graphical user interface with variable settings. The blue line in Fig. 4 represented original scaled NDVI and the red line was the fitted NDVI values, which had close match with the valid NDVI values and did not considered the cloud contaminated lower NDVI values.

There are total 11 phenology metrics, which could be extracted from NDVI time series using TIMESAT. The present study used small seasonal integral NDVI (SiNDVI) to represent the greenness of the forest. The start of the growing season was defined as the time point at which the value of the fitted function had first crossed 20% of the distance between minimum and maximum at the rising limb. Likewise, the time point of the fitted function first exceeded 20% of the distance between minimum and maximum at the falling limb was considered as the end of the season. The SiNDVI was calculated as the area under the vegetation curve during the growing season and above the mean of the base value. The SiNDVI represents the seasonal greenness of the forest and considered as a robust parameters to assess the changes in the forest cover/greenness. The detailed descriptions of the extraction of crop phenology metrics were discussed in Jönsson and Eklundh (2002).

3.4. Processing of the areas with no phenology

The representative NDVI temporal profiles over zones having no phenology were presented in Fig. 5. Both the zones consist of evergreen or alpine or montane forest type. The zone 4 was intermixed with snow clad areas and persistent cloud cover particularly in the parts of Eastern Himalayas of India, where as zone 5 was mainly intermixed with persistent cloud covering the western ghats of India. Thus the temporal NDVI profiles in these zones were very erratic or do not contain minimum amplitude of phenology response. So, SiNDVI was not considered to be a robust proxy to represent its seasonal greenness in these zones. The seasonal maximum NDVI value was considered to be a better alternative to represent the forest greenness. Thus, seasonal maximum NDVI values pertained to these zones were calculated considering season as May to April.

3.5. Data harmonization using z score

The dynamic range of the SiNDVI and seasonal maximum NDVI were different and need to be brought into same scale for seamless assessment of the persistent changes of the natural vegetation across India. This had been achieved by converting both the parameter into Z score using the following formula:

$$\textbf{Z score} = (x - \mu)/s$$

x is the value of a pixel for a particular year

μ is the temporal mean of the pixel (2001–14)

s is the temporal standard deviation of the pixel (2001–14)

Thus, Z score could retained the variability of the SiNDVI, seasonal maximum NDVI and at the same time brought them into the same scale to produce seamless database to assess the changes in the vegetation greenness.

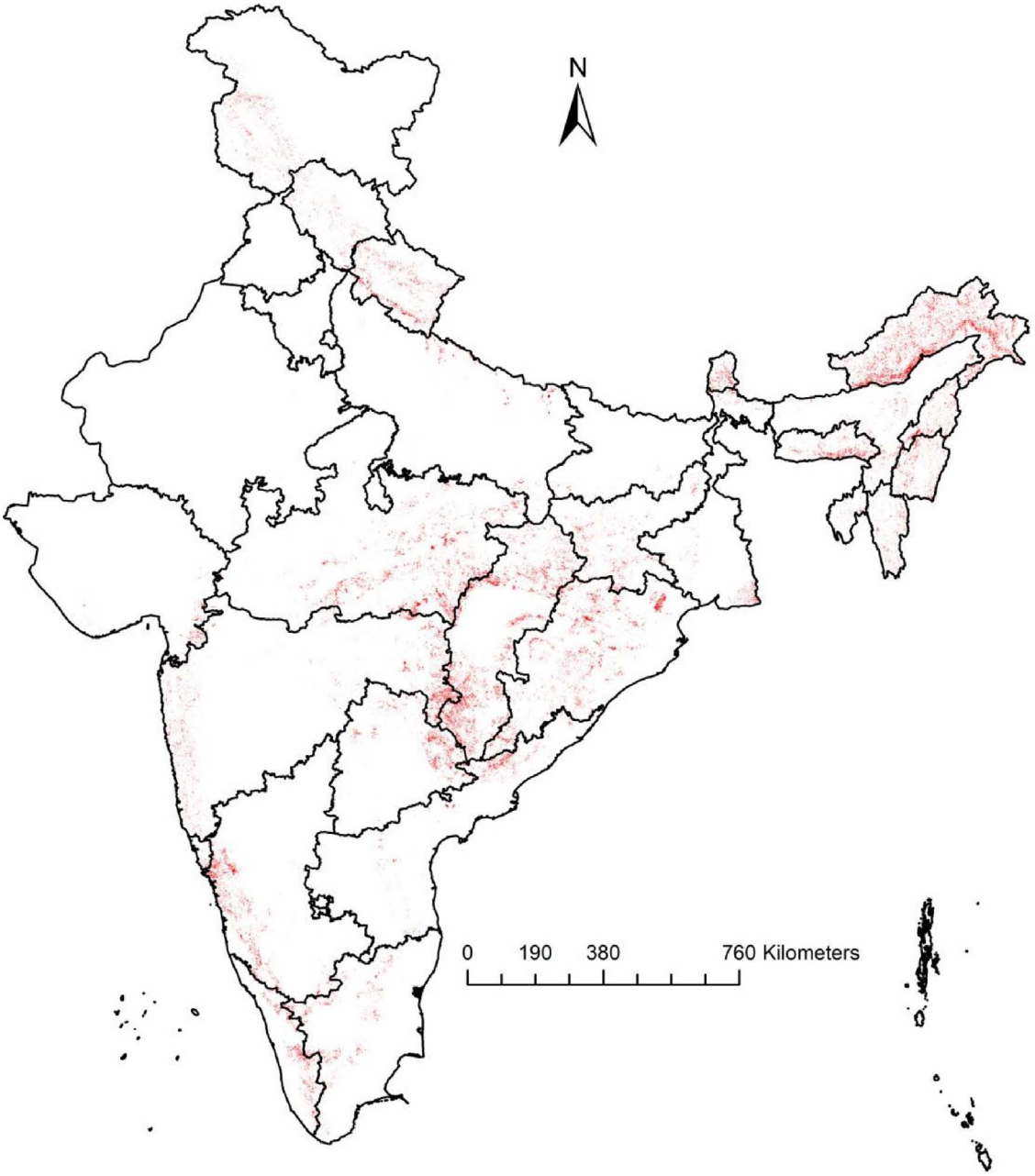

Fig. 6. Spatial patterns of significant (p = 0.1) negative trend of seasonal greenness over the forest areas of India.

3.6. Non parametric trend analysis of vegetation greenness

The Z score calculated from SiNDVI and seasonal maximum NDVI to represent the vegetation greenness of a particular year was further used to calculate non-parametric trend to assess the persistent/gradual change of vegetation greenness during 2001–2014. The Mann-Kendall test was employed to detect presence of trends of vegetation greenness (Mann 1945; Kendall 1975), while Sen's method was used to compute the magnitude of the trend (Sen, 1968a,b). This method has advantages over parametric statistics as it could handle missing values in time series data and the data need not to follow any particular distribution. The Mann-Kendal test finds trend in a time series irrespective of its linearity or nonlinearity. Mann-Kendall method firstly calculates S statistic, which indicates the sum of the difference between the data points indicated in Eq. (1)

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{1}$$

Where, x_i is observed value at time j, x_k is observed value at time k; j is time after time k and n is the length of the data set. The sign of the value is defined as shown in Eq. (2)

$$sgn(x_j - x_k) = \begin{cases} 1 if (x_j - x_k) > 0 \\ 0 if (x_j - x_k) = 0 \\ -1 if (x_j - x_k) < 0 \end{cases} \tag{2}$$

The sign of the value of S indicates the direction of trend. When n > 8, the test statistics S approximately follow normal distribution with mean and variance as shown in eq. 3 and Eq. (4)

$$E(S) = 0 \tag{3}$$

Table 2a
Areas (thousand ha) having significant (p = 0.1) negative trend of seasonal greenness along with different categories of its magnitude over forest types (wet evergreen, dry evergreen, semi evergreen, dry sub-tropical ever green) across the states of India. Percentage areas showed significant negative trend are shown in brackets.

Forest type	States	Area with significant negative trend of seasonal greenness					All India
		Very high	High	Medium	Low	Total	
Wet Evergreen	Karnataka	6.15	76.80	83.40	5.48	171.83 (15.2)	577.43 (13.1)
	Arunachal Pradesh	10.00	92.53	66.43	2.40	171.35 (18.3)	
	Kerala	4.55	46.35	35.70	1.13	87.73 (16.6)	
	Meghalaya	2.55	22.60	21.68	1.23	48.05 (11.9)	
	Tamil Nadu	1.45	12.88	12.05	0.55	26.93 (12.3)	
	Mizoram	0.68	9.33	8.88	0.40	19.28 (3.3)	
	Nagaland	1.18	9.18	6.25	0.48	17.08 (8.7)	
	Assam	0.73	8.73	6.43	0.28	16.15 (6.4)	
	Goa	0.30	3.18	3.50	0.13	7.10 (17.3)	
	Manipur	0.50	3.15	2.18	0.05	5.88 (16.9)	
	West Bengal	0.28	1.60	1.03	0.10	3.00 (6.8)	
	Maharashtra	0.00	1.13	1.05	0.18	2.35 (6.0)	
	Sikkim	0.03	0.25	0.15	–	0.43 (5.5)	
	Tripura	0.05	0.18	0.08	–	0.30 (5.7)	
Dry evergreen	Andhra Pradesh	0.25	1.18	0.68	0.18	2.28 (8.6)	2.40 (6.3)
	Tamil Nadu	–	0.03	0.10	–	0.13 (1.3)	
Semi evergreen	Arunachal Pradesh	4.50	48.63	49.63	3.25	106.00 (19.5)	442.58 (9.5)
	Maharashtra	2.15	38.40	51.00	3.40	94.95 (7.5)	
	Karnataka	0.90	17.30	23.88	2.03	44.10 (8.7)	
	Odisha	1.70	17.45	15.70	0.85	35.70 (21.7)	
	Andhra Pradesh	1.03	15.03	15.68	1.15	32.88(19.6)	
	Kerala	1.05	13.40	17.10	0.83	32.38 (15.3)	
	Meghalaya	0.93	8.35	10.88	0.95	21.10 (8.0)	
	Tamil Nadu	0.63	7.65	9.53	0.68	18.48 (9.9)	
	Assam	0.78	7.65	6.60	0.33	15.35 (3.8)	
	Goa	0.08	3.50	5.88	0.53	9.98 (11.5)	
	Mizoram	0.25	3.73	4.58	0.25	8.80 (1.9)	
	Nagaland	0.23	3.45	4.20	0.43	8.30 (5.9)	
	Uttar Pradesh	0.43	2.68	2.38	0.05	5.53 (10.1)	
	Manipur	0.03	0.93	1.43	0.03	2.40 (2.8)	
	West Bengal	0.08	0.98	0.80	0.13	1.98 (5.9)	
	Sikkim	0.05	0.40	0.80	0.03	1.28 (10.7)	
	Telangana	0.03	0.33	0.63	–	0.98 (17.4)	
	Tripura	–	0.55	0.38	–	0.93 (2.5)	
	Gujarat	–	0.10	0.38	0.03	0.50 (5.9)	
	Uttarakhand	0.03	0.10	0.20	0.03	0.35 (9.0)	
	Himachal Pradesh	–	0.13	0.13	0.05	0.30 (2.1)	
	Jharkhand	–	0.13	0.05	0.03	0.20 (12.5)	
	Dadra Nagar Haveli	–	0.03	0.10	0.03	0.15 (7.6)	
Sub-tropical dry evergreen	Jammu & Kashmir	0.03	0.03	0.18	0.15	0.38 (1.1)	0.38 (1.1)

$$Var(S) = = \frac{n(n-1)(2n+5) - \sum_{i=1}^{q} t_p(t_p-1)(2t_p+5)}{18} \quad (4)$$

Where n refers to number of data points, q refers to number of tied groups (a set of sample data having the same value) and t indicates the number p of data points in the p^{th} group. The statistical significance of S is checked using a test statistic (or Z score). The standardized Mann-Kendall statistics Z follows the standard normal distribution with zero mean and unit variance as shown in Eq. (5)

$$Z = \begin{cases} \frac{s-1}{\sqrt{var(s)}}; S > 0 \\ 0; S = 0 \\ \frac{s+1}{\sqrt{var(s)}}; S < 0 \end{cases} \quad (5)$$

The Mann-Kendall method tests the null hypothesis (H_0),that data indicate no distinct trend against the alternative hypothesis (Hi) that data indicate a trend. Two tailed test is used to decide whether or not the null hypothesis should be rejected in favour of hypothesis test. The null hypothesis, H_0 is tested by the Z test statistic value. A decreasing trend is identified with the negative value of Z and vice-versa. In the present study, H is rejected at p = 0.1 if the absolute value of Z is greater than Z_{tab}, where Z_{tab} is taken from the standard normal cumulative distribution tables. Ordinary Least Square (OLS) method is generally used to estimate the slope of possible linear trend in time series. But OLS would not be able to estimate the magnitude of trend for short noisy time series with outliers or missing data. Sen's slope estimator is robust nonparametric trend operator and is highly immune to gross data error (Sen, 1968a,b). In the present study, magnitude of the trend over time is estimated according to Sen (1968a,b). It is calculated by determining the possible slope between all possible data pairs and then finding the median value as shown in Eq. (6)

$$Q_i = \frac{x_j - x_k}{(j-k)} \quad (6)$$

where, Q_i is slope between data points, i = 1,2 …N and x_j is data measurement at time j, x_k is data measurement at time k, j > k. For n values of the time series of x results, N = n(n − 1)/2 values of Q_i. The sen's estimator is median value of Qi as below:

$$Q = Q_{\left(\frac{N+1}{2}\right)} \quad \text{if N is odd,} \quad (7)$$

$$Q = \frac{1}{2}\left(Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]}\right) \quad \text{if N is even.} \quad (8)$$

3.7. Analysing significant negative trend of forest greenness in the core forest areas

The Mann-Kendal statistics as explained in the previous section

Table 2b
Areas (thousand ha) having significant (p = 0.1) negative trend of seasonal greenness along with different categories of its magnitude over forest types (moist deciduous, dry deciduous) across the states of India. Percentage areas showed significant negative trend are shown in brackets.

Forest type	States	Area with significant negative trend of seasonal greenness					All India
		Very high	High	Medium	Low	Total	
Moist deciduous	Chhatisgarh	3.80	207.05	249.45	7.83	468.13 (17.9)	2067.35 (9.9)
	Odisha	7.83	201.15	192.13	5.23	406.33 (11.3)	
	Maharashtra	0.93	76.70	124.43	3.83	205.88 (13.4)	
	Madhya Pradesh	1.20	68.95	86.33	2.28	158.75 (9.9)	
	Jharkhand	1.08	43.38	52.33	1.40	98.18 (6.4)	
	Uttaranchal	2.58	52.00	37.05	1.08	92.70 (14.7)	
	Manipur	1.48	33.88	40.43	2.33	78.10 (6.1)	
	Karnataka	1.30	30.98	32.00	1.38	65.65 (10.1)	
	Uttar Pradesh	2.58	33.83	22.25	0.55	59.20 (16.0)	
	Tamil Nadu	1.08	24.15	31.95	1.70	58.88 (8.9)	
	Assam	1.58	26.10	29.18	0.95	57.80 (4.1)	
	Arunachal Pradesh	1.58	27.75	24.05	0.63	54.00 (14.6)	
	Nagaland	1.08	18.75	23.90	1.03	44.75 (5.8)	
	Telangana	0.65	17.53	18.73	0.60	37.50 (14.0)	
	Andhra Pradesh	0.65	14.13	19.65	0.83	35.25 (8.9)	
	Kerala	0.35	15.55	17.15	0.48	33.53 (12.4)	
	Gujarat	0.40	10.23	10.00	0.28	20.90 (15.5)	
	Mizoram	0.38	8.80	8.48	0.28	17.93 (2.9)	
	Meghalaya	0.25	6.90	9.08	0.33	16.55 (2.6)	
	West Bengal	0.35	7.85	8.00	0.25	16.45 (6.6)	
	Himachal Pradesh	0.05	6.43	9.50	0.30	16.28 (5.0)	
	Tripura	0.18	5.68	5.20	0.18	11.23 (2.6)	
	Jammu & Kashmir	0.03	1.05	2.68	0.33	4.08 (1.9)	
	Bihar	0.00	1.43	2.45	0.13	4.00 (2.5)	
	Punjab	0.03	0.75	1.35	0.08	2.20 (2.8)	
	Sikkim	–	0.70	1.15	–	1.85 (16.8)	
	Haryana	–	0.18	0.50	–	0.68 (2.6)	
	Goa	–	0.30	0.10	–	0.40 (9.8)	
	Dadra Nagar Haveli	–	0.13	0.10	–	0.23 (7.4)	
Dry deciduous	Madhya Pradesh	4.05	161.00	232.90	10.10	408.05 (6.6)	1407.73 (6.5)
	Chhatisgarh	4.50	141.50	180.03	9.15	335.18 (11.6)	
	Telangana	2.75	77.50	102.45	4.73	187.43 (11.7)	
	Maharashtra	0.50	38.23	74.45	4.33	117.50 (5.4)	
	Odisha	0.90	28.45	37.63	2.63	69.60 (6.4)	
	Andhra Pradesh	0.60	21.65	36.05	2.58	60.88 (3.5)	
	Tamil Nadu	0.58	20.18	29.95	3.10	53.80 (6.0)	
	Jharkhand	0.55	20.50	28.73	1.40	51.18 (7.1)	
	Uttar Pradesh	0.85	13.35	15.68	1.30	31.18 (6.0)	
	Gujarat	0.68	13.20	15.48	0.85	30.20 (3.8)	
	Karnataka	0.28	8.95	13.13	1.00	23.35 (2.2)	
	West Bengal	0.10	5.68	7.05	0.63	13.45 (5.0)	
	Bihar	0.10	4.28	7.25	0.68	12.30 (3.2)	
	Uttarakhand	0.23	3.45	3.60	0.23	7.50 (11.7)	
	Kerala	0.05	0.90	1.08	0.03	2.05 (7.4)	
	Rajasthan	–	0.25	0.70	0.13	1.08 (0.1)	
	Punjab	–	0.20	0.70	0.03	0.93 (2.0)	
	Assam	–	0.20	0.45	0.05	0.73 (5.6)	
	Dadra Nagar Haveli	–	0.18	0.35	0.05	0.58 (8.8)	
	Jammu & Kashmir	–	0.13	0.30	0.03	0.45 (1.1)	
	Haryana	–	0.08	0.08	–	0.15 (0.4)	
	Meghalaya	–	0.03	0.05	–	0.08 (3.5)	
	Arunachal Pradesh	–	0.03	–	–	0.05 (20.0)	
	Tripura	–	0.03	0.03	–	0.05 (2.1)	
	Himachal Pradesh	–	–	0.03	–	0.03 (0.2)	

provides significant negative trend of forest greenness along with its magnitude. The spatial distribution of negative changes could have occurred in the forest edges, isolated patches and in the core areas of the forest. Any negative change in the core forest areas would be of major conservation concern. Thus, forest fragmentation analysis was performed using the Landscape Fragmentation tool in ArcGIS (Vogt et al., 2007). Edge forests, perforated forests and patch forests were indicators of disturbance, thus removed from the analysis to avoid direct anthropogenic influences on vegetation and the core forest areas are considered for significant negative trends over the study period.

3.8. Hotspot analysis of the significant negative trend of seasonal greenness

The hot spot analysis was performed using optimized hotspot analysis tool of ArcGIS (Getis and Ord, 1992; Ord and Getis, 1995). It calculates the Getis-Ord Gi* statistic (G_i^*) for each feature in a dataset, which is a measure of degree of spatial clustering of local sample and how it is different from expected value. It is calculated as the sum of differences between values in the local sample and the mean, and is standardized as Z-score. The equation to calculate Getis-Ord statistics (G_i^*) is as below;

Table 2c
Areas (thousand ha) having significant (p = 0.1) negative trend of seasonal greenness along with different categories of its magnitude over forest types (Montane wet temperate, Himalayan moist temperate, Himalayan dry temperate, Sub-alpine) across the states of India. Percentage areas showed significant negative trend are shown in brackets.

Forest type	States	Area with significant negative trend of seasonal greenness					All India
		Very high	High	Medium	Low	Total	
Montane wet temperate	Arunachal Pradesh	1.85	20.13	24.43	2.45	48.85 (10.2)	90.48 (12.2)
	Nagaland	0.50	6.60	7.00	0.63	14.73 (16.5)	
	Sikkim	0.38	3.58	3.65	0.43	8.03 (22.9)	
	Manipur	0.53	3.75	3.23	0.40	7.90 (14.9)	
	Tamil Nadu	0.43	2.00	2.10	0.25	4.78 (9.2)	
	West Bengal	0.18	1.75	2.35	0.28	4.55 (23.3)	
	Kerala	0.08	0.28	0.45	0.03	0.83 (7.0)	
	Mizoram	–	0.40	0.30	0.08	0.78 (14.4)	
	Karnataka	–	0.05	–	–	0.05 (12.5)	
himalayan moist temperate	Arunachal Pradesh	2.70	61.50	108.05	11.78	184.03 (11.8)	293.80 (11.2)
	Uttaranchal	0.65	20.68	31.80	2.95	56.08 (11.3)	
	Sikkim	0.50	11.23	16.00	1.93	29.65 (24.7)	
	Jammu & Kashmir	0.13	4.08	7.28	0.58	12.05 (8.7)	
	Himachal Pradesh	0.08	3.08	6.75	1.15	11.05 (3.7)	
	West Bengal	–	0.30	0.40	0.08	0.78 15.2)	
	Nagaland	–	0.03	0.15	–	0.18 (10.0)	
Himalayan dry temperate	Jammu & Kashmir	2.75	18.43	11.60	0.68	33.45 (7.5)	60.23 (7.9)
	Arunachal Pradesh	1.18	9.90	6.60	0.18	17.85 (8.0)	
	Uttarakhand	0.18	1.93	1.48	0.00	3.58 (9.8)	
	Himachal Pradesh	0.25	1.55	1.23	0.05	3.08 (6.6)	
	Sikkim	0.15	1.38	0.70	0.05	2.28 (19.0)	
Sub Alpine	Jammu & Kashmir	1.05	8.08	7.73	0.85	17.70 (11.6)	43.95 (7.6)
	Arunachal Pradesh	0.55	4.70	5.38	0.90	11.53 (5.6)	
	Sikkim	0.43	2.23	2.48	0.25	5.38 (8.4)	
	Uttarakhand	0.20	2.43	2.10	0.20	4.93 (6.9)	
	Himachal Pradesh	0.38	1.80	1.93	0.33	4.43 (5.1)	

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \overline{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2]}{n-1}}} \quad (10)$$

Where, x_j is the attribute value for feature j, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of feature and:

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n} \quad (11)$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\overline{X})^2} \quad (12)$$

It resulted in z-scores and *p*-values describing spatial cluster of features with either high or low values. It looked at each feature within the context of neighbouring features. A feature with a high value may not be a statistically significant hot spot, until and unless it is surrounded by other features with high values. A proportional comparison was performed between the local sum (neighbouring) of a feature and the sum of all features. Statistically significant z-score was achieved when the local sum is significantly different from the expected local sum so that it did not resulted of random chance. While positive values of Gi* represent clusters that are, on average, greater than the global mean (Hotspots), the negative values represent clusters that are less than the global mean (Cold spots). In the context of present study, pixels with significant negative trend of seasonal greenness but with different degree of magnitude, were analyzed using G_i^* statistics to identify spatially coherent clusters or hotspots of relatively high magnitude of significant negative trend.

4. Results and discussions

The spatial pattern of significant negative trends of seasonal greenness was presented in Fig. 6. The trend analysis produced magnitude of negative trend across the forest types using Sen's slope. The magnitude of trend was classified into four categories i.e low, medium, high and very high based on the frequency distribution of the Sen's slope specific to different forest types. The dynamic range of the different categories of Sen's slope as mentioned earlier was fixed over the different forest type by dividing the respective frequency distribution into four equal parts. The area statistics of the different categories of significant negative trend over the forest types across different states of India are presented in Table 2a–2d.

4.1. Assessing spatial patterns of significant negative trend of seasonal greenness over different forest types

4.1.1. Wet evergreen forest

The wet evergreen forest has canopy of green foliage throughout the year. It is characterized by evergreen trees of more than 30m height. The forest is made of multi-storied tree structures; shrubs are found close to the ground, followed by short trees and tall trees at the top. Ferns, orchids, mosses and aroids are quite common. This type of forest is mainly found in the high rainfall areas of the Western Ghats, Eastern Himalayas, north-eastern region, and Andaman and Nicobar Islands. Major changes in wet evergreen forest were observed (Table 2a) over Karnataka (171.83 thousand ha) and Arunachal Pradesh (171.35 thousand ha), followed by Kerala (87.73 thousand ha) and Meghalaya (48.05 thousand ha). Karnataka is dominated by the medium category of negative trend, whereas rest of the four states is dominated by high negative changes of the greenness. It is important to note that small states like Goa and Manipur also showed negative changes in greenness over considerable areas of wet evergreen forest i.e. 17.3% and 16.15% respectively. Overall 577.43 thousand ha, which consists of 13.1% of the total wet evergreen forest showed significant negative trend of seasonal greenness.

4.1.2. Tropical dry evergreen forest

Tropical dry evergreen forest is characterized by short boles, spreading crowns, hard-leaved evergreen trees with fragrant flowers along with few deciduous trees. It is found in parts of Eastern Ghats and

Table 2d
Areas (thousand ha) having significant (p = 0.1) negative trend of seasonal greenness along with different categories of its magnitude over forest types (Mangrove, Thorn, Sub-tropical Broad Leaved, Sub-tropical pine) across the states of India. Percentage areas showed significant negative trend are shown in brackets.

Forest type	States	Area with significant negative trend of seasonal greenness					All India
		Very high	High	Medium	Low	Total	
Mangrove	West Bengal	8.68	29.20	3.70	–	41.58 (19.6)	50.55 (15.6)
	Odisha	1.35	3.08	0.18	–	4.60 (28.5)	
	Maharashtra	0.40	1.53	0.15	–	2.08 (8.6)	
	Gujarat	0.28	1.03	0.08	–	1.38 (3.2)	
	Andhra Pradesh	0.23	0.63	0.05	–	0.90 (3.4)	
	Tamil Nadu	–	0.03	–	–	0.03 (1.4)	
Thorn	Tamil Nadu	0.18	1.00	1.10	0.45	2.73 (1.9)	4.35 (0.5)
	Uttar Pradesh	0.08	0.15	0.15	0.10	0.48 (0.5)	
	Telangana	0.03	0.05	0.23	0.05	0.35 (0.7)	
	Andhra Pradesh	0.03	0.05	0.18	0.03	0.28 (0.3)	
	Haryana	0.05	0.08	0.05	0.05	0.23 (1.0)	
	Karnataka	–	0.03	0.10	0.05	0.18 (0.6)	
	Rajasthan	–	–	–	0.05	0.05 (0.1)	
	Gujarat	0.03	0.03	–	–	0.05 (0.1)	
	Arunachal Pradesh	0.03	–	–	–	0.03 (6.3)	
Sub-tropical broad leaved	Arunachal Pradesh	9.18	124.18	105.53	5.20	244.08 (17.2)	321.13 (15.6)
	Meghalaya	0.93	11.30	11.53	0.95	24.70 (11.0)	
	Manipur	0.65	6.88	5.78	0.28	13.58 (20.3)	
	Mizoram	0.38	5.75	5.28	0.35	11.75 (10.3)	
	Nagaland	0.43	4.70	3.18	0.10	8.40 (26.7)	
	Assam	0.50	3.85	3.45	0.18	7.98 (15.6)	
	West Bengal	0.13	1.70	1.85	0.08	3.75 (19.2)	
	Uttarakhand	–	0.98	1.08	0.05	2.10 (6.7)	
	Sikkim	0.08	0.98	0.63	0.03	1.70 (9.2)	
	Himachal Pradesh	–	0.43	0.43	0.03	0.88 (1.6)	
	Maharashtra	0.05	0.35	0.35	–	0.75 (10.1)	
	Jammu & Kashmir	–	0.28	0.43	0.03	0.73 (7.3)	
	Karnataka	–	0.10	0.28	0.05	0.43 (7.6)	
	Tamil Nadu	–	0.18	0.08	0.03	0.28 (18.6)	
	Rajasthan	–	0.03	–	–	0.03 (0.3)	
	Kerala	–	0.03	–	–	0.03 (50.0)	
Sub-tropical pine	Jammu & Kashmir	1.63	22.70	25.73	2.20	52.25 (6.3)	140.50 (6.2)
	Uttarakhand	1.05	15.30	19.73	1.93	38.00 (6.3)	
	Himachal Pradesh	1.00	11.83	15.18	0.93	28.93 (4.8)	
	Arunachal Pradesh	0.60	7.08	8.35	0.35	16.38 (11.0)	
	Meghalaya	0.35	1.90	2.00	0.25	4.50 (7.7)	
	Sikkim	–	0.25	0.08	0.00	0.33 (22.4)	
	Manipur	–	0.10	–	–	0.10 (2.5)	
	West Bengal	–	0.03	–	–	0.03 (33.3)	

coastal plains mainly in Andhra Pradesh and Tamil Nadu. Dry evergreen forest occupies limited areas in the southern deccan peninsula and only 2.4 thousand ha showed significant decrease in greenness mainly over state of Andhra Pradesh (Table 2a).

4.1.3. Tropical semi-evergreen forest

Tropical semi-evergreen forest comprises largely of evergreen tree species in top storey and deciduous ones in middle storey. Semi evergreen forest is spread across the India, except north western India. Vast areas of Arunachal Pradesh (106 thousand ha) and Maharashtra (94.95 thousand ha) showed significant decrease in greenness of semi evergreen forest (Table 2a). This was followed by the Karnataka (44.1 thousand ha), Odisha (35.7 thousand ha), Andhra Pradesh (32.88 thousand ha), Kerala (32.38 thousand ha) and in every cases changes of medium intensity were found to be dominating. Overall 442.53 thousand ha of semi evergreen forest showed significant decrease in seasonal greenness.

4.1.4. Subtropical dry evergreen forest

Subtropical dry evergreen forest comprises of small shiny leaved evergreen trees and shrubs including thorny species where more than 75% of trees remain green throughout the year. This type of forests normally have a prolonged hot and dry season. Annual herbs and grasses are commonly observed during monsoon. These forests are found in the foothills of the Himalayas up to an elevation of 1500 m. Sub-tropical dry evergreen forest did not showed negative changes during the time period of the present study (Table 2a).

4.1.5. Tropical moist deciduous forest

Tropical moist deciduous forest is characterized mainly by the deciduous broadleaf trees in top storey along with evergreen shrubs in understorey, with an annual cycle of leaf-on and leaf-off periods. The trees of this kind of forest form irregular top storey. Bamboos, canes and epiphytes are localised in distribution, but climbers are abundant. Majority of the taller trees shed their leaves in the dry season, whereas shorter plants remain green throughout the seasons. The onset of leaf flushing generally starts in late May or early June. Moist deciduous forests occur in all parts of India except Rajasthan and Trans-Himalayas. Significant decrease in greenness of moist deciduous forest was observed over 2067.35 thousand ha i.e. 9.9% of the total area under moist deciduous forest (Table 2b). Chhatisgarh (468.13 thousand ha), Odisha (406.33 thousand ha), Maharashtra (205.88 thousand ha) and Madhya Pradesh (158.75 thousand ha) were the major contributor of it. On the other hand, 16% area of Uttar Pradesh, 15.5% area of Gujarat, 14.7% area of Uttarakhand under moist deciduous forest showed significant decrease in seasonal greenness. Among the different categories of changes, medium category dominated in case of moist deciduous forest.

Table 3
Areas (thousand ha) having significant (p = 0.1) negative trend of seasonal greenness along with different categories of its magnitude within the core forest areas. Percentage areas having significant negative trend are shown in brackets.

Forest type	Area with significant negative trend of seasonal greenness within the core forest areas				Total area
	Very High	High	Medium	Low	
Wet Evergreen	26.25	264.48	227.00	11.28	529.00 (91.1)
Dry Evergreen	0.23	1.00	0.63	0.13	1.98 (82.5)
Semi evergreen	12.33	160.10	184.23	12.40	369.05 (83.4)
Sub-tropical dry evergreen	–	–	0.10	0.10	0.20 (52.6)
Moist deciduous	25.65	774.88	864.28	27.05	1691.85(81.8)
Dry deciduous	12.78	471.58	656.10	34.48	1174.93(83.5)
Mangrove	8.80	29.28	3.40	0.00	41.48 (82.1)
Sub-tropical broad leaved	11.90	152.55	131.08	6.58	302.10 (94.1)
Sub-tropical pine	3.53	41.75	49.00	3.53	97.80 (69.6)
Montane wet temperate	3.73	36.53	41.60	4.20	86.05 (95.1)
Himalayan moist temperate	3.78	92.48	155.55	16.85	268.65 (91.4)
Himalayan dry temperate	3.48	24.55	15.20	0.33	43.55(72.3)
Sub-alpine	1.45	11.28	12.05	1.58	26.35 (59.9)
Thorn	0.23	0.90	0.98	0.50	2.60 (59.8)
Grand total					4635.58

4.1.6. Tropical dry deciduous forest

Tropical dry deciduous forest is represented mainly by deciduous species and found in the drier and semi-arid parts of India. It becomes entirely leafless exposing the below canopy soil for 1–4 months during February to May. The canopy of the trees rarely exceeds 20 m. The species diversity is less as compared to evergreen, semi-evergreen and moist deciduous forests. Canes and palms are absent, epiphytes and ferns are very rare, and climbers are comparatively few. Herbaceous vegetation is quite common. Dry deciduous forest showed significant decrease in greenness over 1407.73 thousand ha i.e. 6.5% of the total area the forest type (Table 2b). Madhya Pradesh (408.05 thousand ha), Chhatisgarh (335.18 thousand ha), Telangana (187.43 thousand ha) and Maharashtra (117.5 thousand ha) occupied lion share of these changes. Whereas significant areas of dry deciduous forest over Odisha (69.6 thousand ha), Andhra Pradesh (60.88 thousand ha), Tamil Nadu (53.8 thousand ha) and Jharkhand (51.18 thousand ha) showed negative trend of its greenness.

4.1.7. Montane wet temperate forest

It is a dense evergreen forest found in the higher altitudes of Eastern Himalayas, North East and Western Ghats mostly above 1500 m. Trees reaches mostly up to 15 m only, have large girth and branching crowns, coriaceous leaves which are red in colour during tender stage. The branches of the trees are covered with mosses, ferns and epiphytes. Woody climbers are commonly found in this forest but conifers are absent. Montane wet temperate forest showed significant decrease in greenness over 90.48 thousand ha i.e. 12.2% of the total forest type (Table 2c). Majority of this changes were found over Arunachal Pradesh (48.85 thousand ha), Nagaland (14.73 thousand ha), Sikkim (8.03 thousand ha) and Manipur (7.9 thousand ha).

4.1.8. Himalayan moist temperate forest

This type of forest is generally dominated by conifers with varying evergreen species which have canopy heights of 20–40 m and found in the Himalayan ranges particularly in the eastern part where rainfall is heavier. The forest has deciduous shrubs as undergrowth and mosses on branches of trees. Luxuriant growth of herbaceous vegetation is found in summer due to snow cover during the winter and monsoon. Nearly 11.2% area of the Himalayan moist temperate forest (293.8 thousand ha) exhibited significant decrease in seasonal greenness. Arunachal Pradesh (184.03 thousand ha), Uttarakhand (56.08 thousand ha) and Sikkim (29.65 thousand ha) contributed major share of these changes.

4.1.9. Himalayan dry temperate forest

Himalayan dry temperate forest is mostly a pure open forest consist of conifers, with varying proportions of xerophytic shrub species. Epiphytes and climbers are rarely present in this type of forest. It is found in the drier regions of Himalayan like inner ranges of Ladakh, Lahul, Sikkim and other parts. Himalayan dry temperate forest showed significant decrease in its greenness (Table 2c) over Jammu & Kashmir (33.45 thousand ha) and Arunachal Pradesh (17.85 thousand ha). Overall, 7.9% of the total Himalayan dry temperate forest i.e. 60.23 thousand ha showed significant negative trend of seasonal greenness.

4.1.10. Sub alpine forest

Sub alpine forest predominately consists of conifers along with small and stunted trees and shrubs. Abundance of epiphytic moss, lichen and ferns are found in this type of forest but climbers are rarely seen. Different species of Rhododendron are found as a major parts of this type of forest. These forests are found in the Himalayas ranges from Kashmir to Arunachal Pradesh at the upper limit of timberline as strips along snow-slides. Sub-alpine forest was found to have negative changes in greenness over 43.95 thousand ha i.e. 7.6% of the area under the forest type (Table 2c). In this case also, Jammu & Kashmir (17.70 thousand ha) and Arunachal Pradesh (11.53 thousand ha) occupied the major share of the changes. It is important to note that, moderate decrease in the seasonal greenness dominated over Himalayan moist temperate and montane wet temperate forests, whereas high decrease in the seasonal greenness was observed in the Himalayan dry temperate and sub-alpine forest.

4.1.11. Mangrove forest

Mangroves are found in coastal belt of India and consisting of halophytic evergreen species which have pneumatophores/stilt roots and vivipary. The species diversity is relatively low. Generally, fruits/seeds of the species are large but lighter than water. Mangroves are mainly distributed along the east coast in Sunderbans, Brahmani-Baitarani, Mahanadi, Godavari, Krishna, Cauvery delta and west coast of Gujarat, Maharashtra and Goa and also in the coastal strip of Andaman and Nicobar Islands. Mangroves are one of the most fragile ecosystems which are highly affected by the rise in sea level, salt balance of estuary, natural disaster like cyclone. The present study showed that 50.55 thousand ha, which is 15.6% of the total mangrove forest, was having significant negative trend of seasonal greenness (Table 2d). Most of the affected areas were found in West Bengal (41.58 thousand ha) with a high magnitude of negative trend.

4.1.12. Tropical thorn forest

Tropical thorn forest is an open forest dominated by thorny, hardwood species. The trees height is generally below 10 m. Species of Acacia are common in these forests. This type of forest is found in Indian desert (parts of Gujarat and Rajasthan), Gangetic plains (Uttar Pradesh), Deccan (Andhra Pradesh, Telangana, Karnataka and Tamil Nadu) and semi-arid region (Rajasthan). In the present study, thorn forest did not show any significant change. Only 4.35 thousand ha was found to have significant decrease in the greenness (Table 2d).

4.1.13. Subtropical broad leaved forest

This forest is a mixture of evergreen and temperate species along with orchids, bamboos and creepers, found mainly in the limited to lower slopes of the Himalayas, North East, Aravallis (Mt. Abu) and Western Ghats. The members of Lauraceae family are predominantly

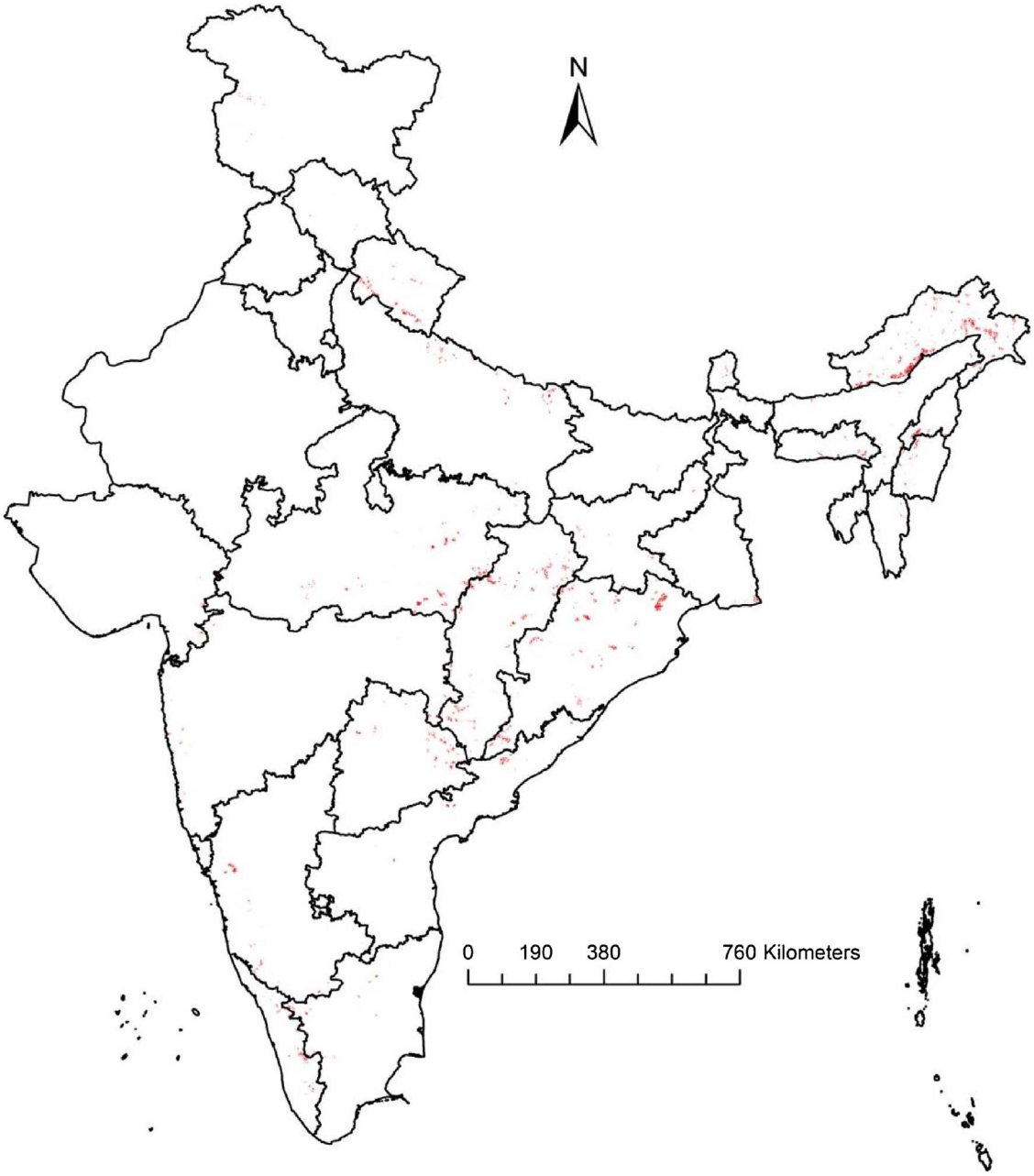

Fig. 7. Spatial patterns of the hotspot (p = 0.1) areas of significant negative trend of seasonal greenness.

found in Western Ghats. The forests in the lower ranges of Eastern Himalayas are reported to be vulnerable due to shifting cultivation and forest fires. Subtropical broad leaved forest was found to have significant decrease in seasonal greenness over 321.13 thousand ha (15.6% of the total forest type: Table 2d), concentrated mainly in the north eastern region of India i.e. Arunachal Pradesh (244.08 thousand ha), Meghalaya (24.7 thousand ha), Manipur (13.58 thousand ha), Mizoram (11.75 thousand ha), Nagaland (8.4 thousand ha) and Assam (7.98 thousand ha).

4.1.14. Subtropical pine forest

Subtropical pine forest areas have predominance of evergreen conifers (pines) in the steep dry slopes of the Western Himalayas, Eastern Himalayas and North East, and considerably influenced by periodical fires. Annual bulbous herbs are common, shrubs are few, but climbers and bamboos are absent in this type of forest. Sub-tropical pine forest was found to have negative trend in it greenness over 140.50 thousand ha mainly concentrated over Jammu & Kashmir, Uttarakhand, Himachal Pradesh and Arunachal Pradesh (Table 2d).

4.2. Assessing significant decrease in seasonal greenness in the core areas of the forest

Spatial analyses of significant negative trends of seasonal greenness during 2001–2014 over different forest types were presented in the previous section. Significant decrease in the seasonal greenness along with its varying magnitude over the core areas of different forest types were presented in Table 3. It was observed that more than 90% of the negative changes of wet evergreen, sub-tropical broad leaved, montane wet temperate, Himalayan moist temperate forest type were found to be in the core forest areas. The percentage areas have gone down to 80–90% in case of dry evergreen, semi evergreen, moist deciduous, dry deciduous and mangrove forest. Sub-tropical dry evergreen, subtropical pine, Himalayan dry temperate, sub-alpine and thorn forests were

Table 4a
Hotspot areas (thousand ha) of significant (p = 0.1) negative trend of seasonal greenness over forest types (wet evergreen, dry evergreen, semi evergreen) across the states of India.

Forest type	States	Hotspot areas	% of hotspot area	Total area of hotspot
Wet Evergreen	Arunachal Pradesh	75.50	44.06	142.00
	Kerala	25.03	28.53	
	Karnataka	15.60	9.08	
	Meghalaya	10.95	22.79	
	Tamil Nadu	3.60	13.37	
	Manipur	3.43	58.30	
	Assam	2.88	17.80	
	Nagaland	2.80	16.40	
	West Bengal	1.08	35.83	
	Mizoram	0.60	3.11	
	Goa	0.53	7.39	
	Tripura	0.03	8.33	
Dry evergreen	Andhra Pradesh	1.85	81.32	1.85
Semi evergreen	Arunachal Pradesh	49.85	47.03	116.88
	Odisha	20.95	58.68	
	Andhra Pradesh	9.35	28.44	
	Maharashtra	6.85	7.21	
	Karnataka	6.30	14.29	
	Assam	5.68	36.97	
	Tamil Nadu	4.63	25.03	
	Kerala	4.13	12.74	
	Meghalaya	4.05	19.19	
	Uttar Pradesh	3.23	58.37	
	Nagaland	0.55	6.63	
	West Bengal	0.53	26.58	
	Tripura	0.18	18.92	
	Goa	0.18	1.75	
	Uttarakhand	0.15	42.86	
	Sikkim	0.13	9.80	
	Manipur	0.13	5.21	
	Jharkhand	0.03	12.50	
	Mizoram	0.03	0.28	

found to have 50–70% areas of the total areas of significant negative trend of seasonal greenness within the core forest areas. Thus, most of the forest types showed more than 80% of the total negative changes in seasonal greenness in the core forest areas. Importantly most of these changes were of high to medium category, signifying the vulnerability of the Indian forest.

4.3. Analysing the hotspots of significant decrease in the seasonal greenness

Along with the total areas affected by significant decrease in the seasonal greenness, it is also important to analyze spatial coherence or aggregation of the affected areas. Towards this effort, hotspot analysis of the spatial patterns of the significant negative trends of the seasonal greenness was performed using Gi* statistics. The statistics helps us to find out the spatial clusters of high negative trends (hotspots), which are statistically significant (p = 0.1). The spatial patterns of the hotspot areas of significant negative trend of seasonal greenness at p = 0.1 was shown in Fig. 7. The hotspot areas identified over different forest types across the states of India were presented in Table 4a–4d.

Out of total 577.43 thousand ha of affected areas, 142 thousand ha were identified as hotspot in wet evergreen forest (Table 4a). These areas were mainly distributed over Arunachal Pradesh (75.50 thousand ha), Kerala (25.03 thousand ha), Karnataka (15.60 thousand ha) and Meghalaya (10.95 thousand ha). In case of dry evergreen forest 1.85 thousand ha out of total 2.4 thousand ha affected areas were found to be under hotspot over Andhra Pradesh. Major hotspot areas of semi evergreen forest were found over Arunachal Pradesh (49.85 thousand ha), Odisha (20.95 thousand ha), Andhra Pradesh (9.35 thousand ha) with a total hotspot areas of 116.88 thousand ha out of total 442.58 thousand ha affected areas.

Table 4b
Hotspot areas (thousand ha) of significant (p = 0.1) negative trend of seasonal greenness over forest types (moist deciduous, dry deciduous) across the states of India. .

Forest type	States	hotspot areas	% of hotspot areas	Total area of hotspot
Moist deciduous	Odisha	139.55	34.34	459.80
	Chhattisgarh	76.78	16.40	
	Uttarakhand	51.23	55.26	
	Uttar Pradesh	33.93	57.31	
	Madhya Pradesh	27.78	17.50	
	Arunachal Pradesh	23.60	43.70	
	Karnataka	14.58	22.20	
	Nagaland	12.38	27.65	
	Assam	12.23	21.15	
	Jharkhand	10.83	11.03	
	Manipur	10.05	12.87	
	Telangana	8.45	22.53	
	Maharashtra	7.78	3.78	
	Tamil Nadu	6.88	11.68	
	Kerala	6.53	19.46	
	Andhra Pradesh	4.75	13.48	
	Mizoram	2.50	13.95	
	Gujarat	2.50	11.96	
	Meghalaya	2.35	14.20	
	Tripura	2.08	18.49	
	West Bengal	1.45	8.81	
	Himachal Pradesh	1.38	8.45	
	Bihar	0.25	6.25	
	Punjab	0.03	1.14	
Dry deciduous	Madhya Pradesh	86.03	21.08	282.88
	Chhattisgarh	82.23	24.53	
	Telangana	48.60	25.93	
	Odisha	12.08	17.35	
	Andhra Pradesh	10.88	17.86	
	Uttar Pradesh	10.28	32.96	
	Gujarat	8.38	27.73	
	Maharashtra	7.90	6.72	
	Tamil Nadu	4.45	8.27	
	Jharkhand	3.63	7.08	
	Uttarakhand	3.05	40.67	
	West Bengal	2.18	16.17	
	Karnataka	1.78	7.60	
	Bihar	1.08	8.74	
	Kerala	0.38	18.29	

Nearly 22.2% of the total areas under significant decrease in the greenness i.e. 459.8 thousand ha were found to be hotspot areas in moist deciduous forest (Table 4b). The hotspot areas of moist deciduous forest were mainly distributed over Odisha (139.55 thousand ha), Chhattisgarh (76.78 thousand ha) and Uttarakhand (51.23 thousand ha). Hotspot areas of dry deciduous forest were found in Madhya Pradesh (86.03 thousand ha), Chhatisgarh (82.23 thousand ha) and Telangana (48.60 thousand ha). The total areas under hotspot in dry deciduous forest was found to be 282.88 thousand ha (nearly 20% of the total affected areas).

The hotspot areas in montane temperate and sub-alpine forests were found to be in the lower side in terms of the percentage of the total affected areas (Table 4). Hotspot areas in montane wet temperate forest was found to be 14.63 thousand ha, which is 16.16% of the total areas under significant negative trend and mainly distributed over Arunachal Pradesh (5.25 thousand ha), Manipur (3.68 thousand ha), Nagaland (2.18 thousand ha). Nearly 12.33% of the areas under significant negative trend of greenness i.e. 36.25 thousand ha were found to be under hotspot in case of himalayan moist temperate forest and majority of these were found over Arunachal Pradesh (26.35 thousand ha). The hotspots over himalayan dry temperate and sub-alpine forest were found to be less comparatively i.e. 5.4 thousand ha (8.9% of the total affected areas) and 2.25 thousand ha (5.11 of the total affected areas) respectively. These are mainly found over Arunachal and Jammu &

Table 4c
Hotspot areas (thousand ha) of significant negative (p = 0.1) trend of seasonal greenness over forest types (Montane wet temperate, Himalayan moist temperate, Himalayan dry temperate, Sub-alpine) across the states of India. .

Forest type	States	Hotspot areas	% of hotspot areas	Total area of hotspot
Montane wet temperate	Arunachal Pradesh	5.25	10.75	14.63
	Manipur	3.68	46.52	
	Nagaland	2.18	14.77	
	Tamil Nadu	1.90	39.79	
	Sikkim	1.33	16.51	
	Mizoram	0.18	22.58	
	Kerala	0.10	12.12	
	West Bengal	0.03	0.55	
Himalayan moist temperate	Arunachal Pradesh	26.35	14.32	36.25
	Uttarakhand	5.75	10.25	
	Sikkim	3.25	10.96	
	Jammu & Kashmir	0.525	4.36	
	Himachal Pradesh	0.2	1.81	
	Nagaland	0.15	85.71	
	Manipur	0.025	50.00	
Himalayan dry temperate	Arunachal Pradesh	2.53	14.15	5.40
	Jammu & Kashmir	2.30	6.88	
	Sikkim	0.53	23.08	
	Himachal Pradesh	0.05	1.63	
Sub Alpine	Jammu & Kashmir	1.33	7.49	2.25
	Arunachal Pradesh	0.45	3.90	
	Sikkim	0.25	4.65	
	Himachal Pradesh	0.15	3.39	
	Uttarakhand	0.08	1.52	

Table 4d
Hotspot areas (thousand ha) of significant (p = 0.1) negative trend of seasonal greenness over forest types (Mangrove, Thorn, Sub-tropical Broad Leaved, Sub-tropical pine) across the states of India.

Forest type	States	Hotspot areas	% of hotspot areas	Total area of hotspot
Mangrove	West Bengal	10.40	25.02	13.10
	Odisha	2.18	47.28	
	Maharashtra	0.30	14.46	
	Andhra Pradesh	0.23	25.00	
Thorn	Tamil Nadu	0.03	0.92	0.03
Sub-tropical broad leaved	Arunachal Pradesh	76.93	31.52	92.98
	Manipur	7.40	54.51	
	Nagaland	2.75	32.74	
	Assam	2.10	26.33	
	Mizoram	1.83	15.53	
	Meghalaya	1.18	4.76	
	West Bengal	0.25	6.67	
	Tamil Nadu	0.25	90.91	
	Sikkim	0.20	11.76	
	Uttarakhand	0.08	3.57	
	Karnataka	0.03	5.88	
Sub-tropical pine	Jammu & Kashmir	3.50	6.70	9.28
	Arunachal Pradesh	3.30	20.15	
	Uttarakhand	1.53	4.01	
	Himachal Pradesh	0.55	1.90	
	Meghalaya	0.23	5.00	
	Sikkim	0.18	53.85	

Kashmir.

The mangrove forest was found to show hotspot areas of 13.1 thousand ha, which is 25.9% of the total areas of significant decrease in greenness (Table 4d). Major hotspots were found in West Bengal (10.40 thousand ha). On the other hand sub-tropical broad leaved forest showed major hotspots over Arunachal Pradesh (76.93 thousand ha) with a total hot spot areas of 92.98 thousand ha (28.95% of the total areas under significant negative trend). Total area under hotspot over thorn and subtropical pine forest were found to be insignificant.

4.4. Hotspots of significant decrease in the seasonal greenness over the large protected areas of India

Spatial patterns of hotspots of significant decrease in the seasonal greenness were further analyzed over the protected areas (Wildlife sanctuary, National park, Conservation Reserve etc.). The Large protected areas (more than 500 km^2 or 50 thousand ha) experiencing spatially coherent significant negative changes in the seasonal greenness (hotspots) were identified and listed in Table 5. Total 20 large protected areas were found to have experienced significant negative change of seasonal greenness. Similipal wild life sanctuary of Odisha showed maximum areas under the hotspot *i.e.* 48.6 thousand ha followed by the Rajaji national park of Uttarakhand (14.5 thousand ha), Achanakmar wildlife sanctuary of Chhatisgarh (13.5 thousand ha), Sundarban of West Bengal (9.3 thousand ha). Other protected areas also showed similar negative changes with comparatively lesser spatial extent as depicted in Table 5. Most of these protected areas belong to very fragile ecosystem and biodiversity hotspots. Any changes in the forest greenness or degradation of these areas lead to rapid deterioration of the ecosystem services. The result of present study could provide firsthand information of prioritization and planning of conservation/restoration of the protected areas based on time series satellite observations.

5. Conclusions

The present study was conducted to find out persistent negative changes in the forest vigour during the time frame of 2001–2014. Towards this effort, 8-day composite MODIS NDVI (500 m) data for the selected time period were processed to extract small seasonal integral NDVI as a surrogate of forest greenness. The areas which were invariant to harmonic pattern of greenness such as evergreen forest, seasonal maximum value of NDVI were considered to be a proxy of forest greenness. Both the surrogates were converted into Z score to bring them into same scale. Non-parametric trend analysis was performed on the time series of forest greenness to obtainthe spatial patterns of significant (p = 0.1) negative trend of forest greenness. Optimized hotspot analysis was performed on the negative changes to get the spatial clusters of high magnitude of decrease in the forest greenness.

It was observed from the present study that moist deciduous forest showed significant negative changes in forest greenness in maximum areas (2067.35 thousand ha) followed by dry deciduous forest (1407.73 thousand ha). Nearly 80% of these changes took place in the core forest areas. Odisha, Chhattisgarh, Madhya Pradesh, Telangana, Uttarakhand were reported to have hotspots of negative changes over the deciduous forest.

Wet evergreen forest was found to have significant negative changes in its greenness over 577.43 thousand ha and more than 90% of it occurred within the core area of wet evergreen forest. The hot spot areas of it were mainly distributed over Arunachal Pradesh, Kerala, Karnataka and Meghalaya. Semi evergreen forest also showed decreased forest greenness over vast areas of 442.58 thousand ha, hotspot being Arunachal Pradesh and Odisha. At least 83% of these changes were found to be in the core areas.

Mangrove forest showed decrease in its greenness over 15.6% of its total area i.e. 50.55 thousand ha, and 83% of it was in the core forest

Table 5
Hotspot areas (thousand ha) of significant (p = 0.1) negative trend of seasonal greenness over large protected areas (> 50 thousand ha or 500 km2) of India.

Protected Area	Designation	State	Area under hotspot (,000 ha)
Similipal	Wildlife Sanctuary	Odisha	48.6
Rajaji	National Park	Uttarakhand	14.5
Achanakmar	Wildlife Sanctuary	Chhattisgarh	13.5
Sundarban	Wildlife Sanctuary	West Bengal	9.3
Eturnagaram	Wildlife Sanctuary	Telangana	6.8
Pakhal	Wildlife Sanctuary	Telangana	5.1
Shoolpaneswar	Wildlife Sanctuary	Gujarat	5.0
Satkosia Gorge	Wildlife Sanctuary	Odisha	4.8
Namdapha	National Park	Arunachal Pradesh	4.4
Kinnerasani	Wildlife Sanctuary	Telangana	4.4
Palamau	Wildlife Sanctuary	Jharkhand	3.1
Khangchendzonga	National Park	Sikkim	2.2
Biligiri Rangaswami Temple	Wildlife Sanctuary	Karnataka	2.0
Kamlang	Wildlife Sanctuary	Arunachal Pradesh	2.0
Indira Gandhi (Annamalai)	Wildlife Sanctuary	Tamil nadu	1.9
Manas	National Park	Assam	1.6
Pawalgarh	Conservation Reserve	Uttarakhand	1.5
Periyar	Wildlife Sanctuary	Kerala	1.4
Dibang	Wildlife Sanctuary	Arunachal Pradesh	1.4
Pakke (Pakhui)	Wildlife Sanctuary	Arunachal Pradesh	1.4

area. West Bengal was identified as hotspot of mangrove degradation. Sub-tropical broad leaved forest, which is known to be affected by shifting cultivation and forest fire, also showed significant negative change of its greenness over 15.6% of the total areas i.e. 321.13 thousand ha. Nearly, 94% of it was in the core forest areas. Manipur, Nagaland, Mizoram, Meghalaya, Assam along with Arunachal Pradesh were found to be the hot spot areas. Sub-alpine forest also showed decrease in its greenness over 140.50 thousand ha, but only 60% of it was found within the core forest areas. The hotspots were found mainly in Jammu & Kashmir, Arunachal Pradesh and Uttarakhand.

Significant decrease in the greenness of montane wet forest was observed over 12.2% of its area i.e. 90.48 and nearly 95% were in the core areas. Manipur, Tamil Nadu, Mizoram, Sikkim and Arunachal Pradesh were found to be its hotspots. Himalayan moist temperate forest also showed significant negative changes in greenness over 293. 8 thousand ha, 91% of the cases were in the core areas. Arunachal Pradesh and Uttarakhand were the hotspots of it. Other forest types did not show negative changes in greenness over vast areas, thus remained to be insignificant.

The present study demonstrated the capability of satellite observations to find out persistent changes in the highly dynamic parameter like forest greenness over decadal scale. The study also reported large protected areas experiencing spatially coherent significant negative change of seasonal greenness. Hence, the results of the present study could be useful in prioritization and planning of conservation measures of forests of India. The future study should focus on the causal analysis of the decrease of forest greenness particularly partitioning of climatic and anthropogenic influences over forest greenness.

Acknowledgments

The present work has been carried out as part of Technology Development Project of National Remote Sensing Centre. The TIMESAT 3.2 software is available online in http://web.nateko.lu.se/timesat/timesat.asp. Dr. C S Jha, Group Director, Forestry an Ecology Group, NRSC is duly acknowledged for his suggestions . We also thank the anonymous reviewers and editor for their valuable comments which have significantly improved the manuscript.

References

Chakraborty, A., Seshasai, M.V.R., Dadhwal, V.K., 2014. Geo-spatial analysis of temporal trends of crop phenology metrics over India and its relationship with rainfall parameters. Environ. Monit. Assess. 186 (7), 4531–4542.

Cleland, E.E., Chuine, I., Menzel, A., 2007. Shifting plant phenology in response to global change. Trends Ecol. Evol. 22 (7), 357–365.

Díaz, S., Fargione, J., Stuart Chapin III, F., Tilman, D., 2006. Biodiversity loss threatens human well-being. PLoS Biol. 4 (8), e277.

De Beur, K.M., Henebry, G.M., 2004. Land surface phenology, climatic variation, and institutional change: analyzing agricultural land cover change in Kazakhstan. Remote Sens. Environ. 89 (4), 497–509.

Eklundh, L., Jönsson, P., 2012. TIMESAT 3.2 with Parallel Processing – Software Manual. Lund University, pp. 88.

FAO, 2011. Assessing forest degradation ?towards the development of globally applicable guidelines. Forest Resources Assessment Working Paper 177. Food and Agriculture Organization of the United Nations (Rome).

Fang, J.Y., Piao, S.L., He, J.S., 2003. Vegetation activities is strengthened during the past 22 years in China. Sci. China (Series C) 33 (6), 554–565 (in Chinese).

Fisher, J.I., Richarson, A.D., Mustard, J.F., 2007. Phenology model from surface meteorology does not capture satellite based green-up estimation. Glob. Change Biol. 13 (7), 707–721.

Getis, A., Ord, J.K., 1992. The analysis of spatial association by use of distance statistics. Geogr. Anal. 24 (3), 189–206.

Gordo, O., Sanz, J.J., 2009. Long-term temporal changes of plant phenology in the western Mediterranean. Glob. Change Biol. 15 (8), 1930–1948.

Heumann, B.W., Seaquist, J.W., Eklundh, L., Jonsson, J., 2007. AVHRR derived phenological change in the Sahel and Soudan, Africa, 1982–2005. Remote Sens. Environ. 108 (4), 385–392.

Jönsson, P., Eklundh, L., 2002. Seasonality extraction by function fitting to time-series of satellite sensor data. IEEE Trans. Geosci. Remote Sens. 40 (8), 1824–1832.

Jönsson, P., Eklundh, L., 2004. TIMESAT–a program for analyzing time series of satellite sensor data. Comput. Geosci. 30 (8), 833–845.

Kaly, U., Pratt, C., Howorth, R., 2002. Towards managing environmental vulnerability in small island developing states (SIDS). SOPAC Miscellaneous Report 461. pp. 16.

Kendall, M.G., 1975. Rank Correlation Methods, fourth. Charles Griffin, London, UK.

Lee, R., Yu, F., Price, K.P., Ellis, J., Shi, P., 2002. Evaluating vegetation phenological pattern in inner Mongolia using NDVI time series analysis. Int. J. Remote Sens. 23 (12), 2505–2512.

Lin, L., Sills, E., Cheshire, H., 2014. Targeting areas for reducing emissions from deforestation and forest degradation (REDD +) projects in Tanzania. Global Environ. Change 24, 277–286.

Mann, H.B., 1945. Non-parametric tests against trend. Econometrica 13, 245–259.

Menzel, A., Estrella, N., Fabian, P., 2001. Spatial and temporal variability of the phenological seasons in Germany from 1951 to 1996. Glob. Change Biol. 7 (6), 657–666.

Midha, N., Mathur, P.K., 2010. Assessment of forest fragmentation in the conservation priority Dudhwa Landscape India using FRAGSTATS computed class level metrics. J. Indian Soc. Remote Sens. 38, 487–500.

Ord, J.K., Getis, A., 1995. Local spatial autocorrelation statistics: distributional issues and an application. Geogr. Anal. 27 (4), 286–306.

Penuelas, J., Fiella, I., 2001. Response to a warming world. Science 294 (5543), 793–794.

Piao, S.L., Fang, J.Y., Zhou, L.M., Ciais, P., Zhu, B., 2006. Variation in satellite derived phenology on China's temperate vegetation. Glob. Change Biol. 12 (4), 672–685.

Reddy, C.S., Dutta, K., Jha, C.S., 2013a. Analysing the gross and net deforestation rates in India. Curr. Sci. 105, 1492–1500.

Reddy, C.S., Sreelekshmi, S., Jha, C.S., Dadhwal, V.K., 2013b. National assessment of forest fragmentation in India: landscape indices as measures of the effects of fragmentation and forest cover change. Ecol. Eng. 60, 453–464.

Reddy, C.S., Jha, C.S., Diwakar, P.G., Dadhwal, V.K., 2015. Nationwide classification of forest type map of India using remote sensing and GIS. Environ. Monit. Assess. 187 (12), 1–30.

Reddy, C.S., Jha, C.S., Dadhwal, V.K., 2016. Quantification and monitoring of

deforestation in India over eight decades (1930–2013). Biodivers. Conserv. 25, 93–116.
Schaber, J., Badeck, F.W., 2003. Physiology based phenology models for forest tree species in Germany. Int. J. Biometeorol. 47 (4), 193–201.
Sen, P.K., 1968a. Estimation of regression coefficients based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389.
Sen, P.K., 1968b. Estimation of regression coefficients based on Kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389.
Soudani, K., Maire, G., Dufrene, E., 2008. Evaluation of the onset of greening-up in temperate deciduous broadleaf forests derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data. Remote Sens. Environ. 112 (5), 2643–2655.
Stockli, R., Vidale, P.L., 2004. European plant phenology and climate as seen in a 20 year AVHRR land surface parameters dataset. Int. J. Remote Sens. 25 (17), 3303–3330.
Vogt, P., Riitters, K., Estreguil, C., Kozak, J., Wade, T., Wickham, J., 2007. Mapping spatial patterns with morphological image processing. Landsc. Ecol. 22, 171–177.
White, M.A., Thornton, P.E., Running, S.W., 1997. A continental phenology model for monitoring vegetation response to interannual climatic variability. Glob. Biogeochem. Cycles 11 (3), 217–234.
Zhou, L.M., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N.V., Myneni, R., 2001. Variation in northern vegetation activity inferred from satellite data of vegetation index during 1981–1999. J. Geophys. Res. Atmos. 106 (D17), 20069–20083.